Baryon Loading of Gamma Ray Bursts by Pick-up Neutrons

Amir Levinson[1] and David Eichler[2]

ABSTRACT

It is proposed that the baryons in gamma ray burst (GRB) fireballs originate as "pick-up" neutrons that leak in sideways from surrounding baryonic matter and convert to protons in a collision avalanche. The asymptotic Lorentz factor is estimated, and, in the absence of collimation, is shown to be angle dependent. Reasonable agreement is obtained with existing limits on the GRB baryonic component. The charged decay and collision products of the neutrons become ultrarelativistic immediately, and a UHE neutrino burst is produced with an efficiency that can exceed 0.5. Other signatures may include lithium, beryllium and/or boron lines in the supernova remnants associated with GRB's and high polarization of the gamma rays.

1. Introduction

An outstanding question in GRB fireballs is the fraction of baryons within them. It is suspected that this fraction is low, because they seem to expand with ultra-relativistic Lorentz factors, $\Gamma \geq 10^2$. While the striking paucity of baryons could be accounted for by invoking energy release on field lines where baryons are confined, say by an event horizon or strong binding to strange quark matter, the question would then arise as to whether the mechanism that enforces baryon purity would be so effective that there would be none whatsoever in the fireball.

This is possible; the fireball could consist of just pairs, gamma rays, and low frequency Poynting flux, but then another question would arise: How do the pairs survive recombination while expanding from an extremely compact region? Were the fireball adiabatically expanding, baryon-free and thermal (Paczynski 1986, Goodman 1986), the e^+e^- pairs would mostly annihilate at an internal temperature of about 15 KeV, corresponding to a radius of not much more than $\sim 10^9$ cm. By contrast, proton-electron pairs would face no such problem, but would raise the first question: If there are so few, why are there any at all? [Note

[1]School of Physics & Astronomy, Tel Aviv University, Tel Aviv 69978, Israel; Levinson@wise.tau.ac.il

[2]Physics Department, Ben-Gurion University, Beer-Sheva 84105, Israel; eichler@bgumail.bgu.ac.il

that the afterglow from the giant Aug. 27, 1998 flare (Frail, Kulkarni, and Bloom 1999) from SGR 1900+14 was sufficiently weak that the outburst seems to have not put much of its energy into escaping pairs (Eichler 2002), in marked contrast to long, cosmologically distant GRB's. This serves as a reminder that a material fireball that mostly survives the compact regions of its origin is not to be taken for granted.]

A theory of baryon content in GRB fireballs could answer these questions. In this letter we attempt to estimate the baryon content that would arise if the fireball originated entirely on magnetic field lines that connect to an event horizon (or anything equally effective in enforcing total baryon purity). We assume that the origin of the baryons is leakage in the form of neutrons crossing from baryon rich field lines to the baryon free outflow (Eichler and Levinson, 1999, hereafter EL). The freshly picked-up neutrons are extremely energetic in the frame of the outflow, and this creates the possibility of creating very energetic ($10^9 \leq E \geq 10^{15}$eV) pions and neutrinos. The analysis of neutron pick-up and neutrino production rates and energies is somewhat similar to that of EL, but here we note a particular instability that exists in this situation: a collisional avalanche. This leads to particularly efficient neutron pick-up and neutrino production.

Neutrons and neutrinos have also been discussed by other authors. Derishev et al. (1999a,b) argued that roughly equal numbers of neutrons and protons should be present in the fireball, and studied the consequences for the hydrodynamics and emission during the prompt and afterglow phases (see also Beloborodov 2002). They proposed that decoupling of the neutrons during the acceleration of the fireball may lead to a burst of $\sim$ 10 GeV neutrinos through inelastic scattering (see also Bahcall and Meszaros 2000). In all the work cited above, the mechanism of baryon contamination is not addressed. The authors merely assume that the baryon content of the fireball is fixed by some mechanism on the smallest scales, prior to its acceleration. Lemoine (2002) reexamined the conditions under which the neutrons in the fireball may remain free and concluded that fusion of neutrons and protons to ^{4}He should precede decoupling if the dynamical timescale exceeds 10^{-4} s (cf. Beloborodov 2002). He then argued that this would lead to a dramatic suppression of the density of free neutrons and, consequently, neutrino emission. However, he did not discuss the possibility of viscous heating at the interface between the fireball and its surroundings. In what follows we consider this possibility and argue that baryonic contamination can occur on much larger scales ($\sim 10^{10}$ cm) via diffusion of neutrons from a baryon rich wind into the baryon free fireball.

Additional baryon loading may arise from mixing, owing to hydrodynamic instabilities at the interface between the baryon poor jet (BPJ) and the baryon rich outflow (BRW) or the enveloping material of the host star. However, the degree of mixing may depend strongly on changes in the magnetic topology, which cannot be easily assessed. Moreover, it is unlikely that it could load all but the outmost layers of the BPJ when the hydrodynamic crossing time scale for the dense, outer material exceeds the proper expansion timescale of the BPJ.

2. Wind ejection

In GRB scenarios that invoke a stellar type progenitor, the ejection of a baryon poor fireball follows a catastrophic event that results in the formation of a system consisting of a compact object surrounded by a hot disk or torus. Here we assume that the fireball emanates from the immediate vicinity of the compact object (a black hole, say) essentially devoid of baryons. This degree of baryon purity is natural if the fireball is generated on field lines that thread the black hole, either by neutrino annihilation or by extraction of the black hole rotational energy (Levinson and Eichler 1993).

During the ejection of the fireball, the matter in the central parts is maintained at temperatures well above 1 MeV, at which emission of MeV neutrinos is the dominant cooling mechanism. Neutrinos escaping from the inner parts of the torus heat the surface layers and drive a powerful, baryon rich wind that propagates at a sub-relativistic speed, and confines the baryon poor fireball. Critical point analysis (van Putten & Levinson 2003, see also Levinson and Eichler 1993) yields an estimate for the baryon rich wind luminosity of

$$L_w \simeq 10^{49.5}\beta_{sc}T_{t10}^4 A_{13} \ \ \mathrm{erg\ s^{-1}}, \tag{1}$$

and for the corresponding mass loss rate of

$$\dot{M} = 2L_w/3a_{sc}^2 \simeq 10^{30} L_{w51}\beta_{sc}^{-2} \ \ \mathrm{gr\ s^{-1}}, \tag{2}$$

where $A = 10^{13}A_{13}$ cm^2 is the surface area of the torus, $T_t = 10^{10}T_{t10}$ K is the torus temperature and $a_{sc} = \beta_{sc}c \simeq 10^{10}(M/M_\odot)^{1/2}(r_c/10^6\ \mathrm{cm})^{-1/2}$ cm s^{-1} is the sound speed at the wind critical point, with M being the mass of the compact object, and r_c the radius of the critical point. For a temperature of 4 MeV, a wind luminosity of $\sim 10^{51}$ erg s^{-1} is expected.

The large optical depth of the expelled wind ($\tau_T \sim 10^8 L_{w51}/r_{10}$) and the extremely short cooling time render the wind pressure radiation dominated. The determination of the wind's temperature and density profiles beyond the critical point requires quantitative treatment of wind acceleration in the supercritical region. Assuming for simplicity that the wind velocity $v_w = \beta_w c$ is constant, we obtain a wind temperature

$$T_w \simeq 10^{8.5} L_{w51}^{1/4}\beta_w^{-1/4}(\psi^2-\theta^2)^{-1/4} r_{10}^{-1/2} \ \ \mathrm{K}, \tag{3}$$

and baryon density

$$n_p = 10^{23} L_{w51}/r_{10}^2 \beta_w^3 (\psi^2 - \theta^2) \ \ \mathrm{cm}^{-3}, \tag{4}$$

where ψ is the opening angle of the baryon rich wind (which, as argued below, may be collimated).

If the explosion occurs inside a star, as in the collapsar scenario for GRB's, both the fireball and the surrounding baryon rich wind must advance first through the stellar core before they break out. During this stage they both may be collimated by the kinetic pressure of the core. As they advance through the star, the BPJ and the baryon rich wind each drives a forward shock that accelerates the stellar material. It is reasonable to assume that the BPJ and the baryon rich wind have similar isotropic equivalent luminosities in which case we expect their head velocities to be roughly the same. The temperature of the shocked wind plasma (behind the reverse shock) is given approximately by eq. (3), upon replacing β_w with β_h. Eventually, the BPJ breaks through the host star's envelope if there is one. Otherwise we would not observe the GRB it is supposed to produce. ¿From the point of view of neutrino production, however, the pre-breakout stage may also be important.

3. The neutron content of the torus wind

If the torus is a remnant of a degenerate star, then it contains nearly half its mass in neutrons. At temperatures above the dissociation temperature of the nuclei (0.5 - 0.7 MeV) the neutrons and protons become free. The neutron to proton ratio ξ_n would then either be the initial value, or, if the weak interaction equilibration time

$$t_{weak} \simeq 5 \times 10^{-2} (T/3\mathrm{MeV})^{-5} \ \ s \tag{5}$$

is shorter than the outflow time, t_{exp}, the equilibrium value, $\xi_n \simeq \exp[(m_p - m_n)/T]$, where m_i is the mass of species i ($i = n, p$). As noted by Derishev et al. (1999b), in the latter case neutrons will be effectively produced through the reaction $p + e^- \to n + \nu$, even if the initial torus composition is predominantly hydrogen. If freeze-out of the weak interaction occurs at $T > (m_n - m_p) \simeq 1$ MeV, then $\xi_n \sim 1$ is generally expected.

Above the critical point, the temperature in the wind declines with radius. Once it drops below about $T_{rec} \simeq 77$ keV (depending weakly on density) the free protons and neutrons will recombine to form deuterium. The reaction rate for deuterium formation is $< \sigma_d v > \simeq 5 \times 10^{-20}$ cm^3 s^{-1}. The corresponding recombination time is then given by

$$t_{rec} \simeq 10^{-3.5} (\psi^2 - \theta^2) \beta_w^3 r_{10}^2 L_{w51}^{-1} \ \ s, \tag{6}$$

where eq. (4) has been used. Recombination will be effective at radii

$$r_{10} < 10^3 L_{w51} \beta_w^{-4} (\psi^2 - \theta^2)^{-1} \tag{7}$$

at which $t_{rec} << t_{exp}$, provided the temperature there is below T_{rec}. Given $T_{rec} \simeq 77$ keV and equation (3)) we conclude that the radius below which free neutrons can exist in the wind is

$$r_n \simeq 2 \times 10^9 L_{w51}^{1/2} (\psi^2 - \theta^2)^{-1/2} \beta_w^{-1/2} \ \ \text{cm}. \tag{8}$$

For reasonable wind parameters, r_n should lie in the range between a few times 10^9 to a few times 10^{11} cm.

While we have assumed that the BPJ is ensheathed by a neutron-rich outflow which we expect exists, we could, for the purposes of the following discussion, assume that the BPJ is in direct contact with the envelope of the host star that collimates it. Neutrons would be freed up at the interface because the inner wall of the envelope would be heated by the BPJ.

4. Neutron pick-up

The free protons and neutrons in the wind are coupled by nuclear elastic scattering. At the temperatures of interest the corresponding rate is $< \sigma_{el} v > \simeq < \sigma_0 c >= 10^{-15}$ cm^3 s^{-1}, independent of center of mass energy.

The flux of neutrons diffusing into the BPJ from the interface separating the BPJ and the baryon rich wind is given by $J_D(r) = \lambda_{np} v_{is} \partial n_n / \partial x = \lambda_{np} v_{is} (n_n/l)$, where $v_{is} = \beta_{is} c = (kT/m_p)^{1/2}$ the ion thermal speed (not to be confused with the sound speed of the radiation dominated plasma), $\lambda_{np} = \beta_{is}/(n_p \sigma_0)$ is the mean free path for np collisions, x denotes the cylindrical radius, and l the gradient length scale (which may vary with r).

Assuming that the boundary between the BPJ and baryon rich wind is very sharp at the BPJ injection radius ($r_0 \sim 10^7$ cm), the gradient length scale at some larger radius r is $l \simeq (\lambda_{np} v_{is} t_{exp})^{1/2}$ with $t_{exp} = r/v_w$ being the wind expansion time. The total number of neutrons diffusing into the BPJ below some radius r is given by $N_{diff}(r) \simeq 2\pi\theta r^2 t_{exp} J_D(r) = 2\pi\theta r^2 l n_n$. Combining the above results one finds,

$$N_{diff}(r) = 2\pi\theta \frac{\beta_{is}}{\beta_w^{1/2}} n_n \frac{r^{5/2}}{\sqrt{n_p \sigma_0}} \simeq 10^{50} \xi_n [(\psi/\theta)^2 - 1]^{-1/2} (\beta_{is}/\beta_w^2) r_{10}^{3/2} L_{w51}^{1/2}, \tag{9}$$

where $\xi_n = n_n/n_p$.

If the density gradient length scale, l, at the BPJ baryon rich wind interface is larger than assumed above, e.g., as a result of some mixing, then the gradient would be smeared and the diffusive flux would be reduced, but presumably advection would replace it and keep the neutron-proton mixture hot. It is hard to see how mixing could penetrate to the BPJ center without disrupting the BPJ entirely, so any mixing would be restricted by this consideration to load only the periphery of the BPJ.

Now the fraction of neutrons drifting through the BPJ that decay, $t_{\rm cross}/\tau_n \simeq 10^{-3.5}\theta\beta_{is}^{-1}r_{10}$, where $t_{cross} = \theta r/v_{is}$ is the BPJ crossing time and $\tau_n = 900$ s is the neutron lifetime, is small. However, each decay liberates a proton that generates more protons via collisions with the undecayed neutrons. The proton fraction thus grows exponentially in what we term a collision avalanche, until becoming comparable to the neutron fraction. To estimate the growth length of the shower, we note that the density of target neutrons inside the BPJ (static in the Lab frame) is $(t_{cross}/t_{exp})(N_{diff}/\pi\theta^2 r^3)$, and the optical depth for a collision of a picked-up baryon with the target neutrons is

$$\tau_{np} = \sigma_{np} r(t_{cross}/t_{exp})(N_{diff}/\pi\theta^2 r^3) = 10^{4.5}\beta_w^{1/2}\psi^{-1}r_{10}^{-1/2}L_{w51}^{1/2}, \tag{10}$$

where a cross section for inelastic pn collisions of $\sigma_{pn} = 40$ mb has been adopted (Hagiwara et al. 2002). Evidently, the growth length of the shower is much shorter than the injection radius and it will saturate already at the base of the BPJ. At this point every neutron diffusing into the BPJ is picked up via a collision with a fast baryon coming from below.

Combining equations (8) and (9), and taking $\beta_{is} = 10^{-2}$ (the ion thermal speed at the recombination temperature) yields the total number of neutrons picked up by the BPJ:

$$N_{cap} = N_{diff}(r = r_n) \simeq 10^{47}\xi_n\theta(\psi^2 - \theta^2)^{-5/4}\beta_w^{-11/4}L_{w51}^{5/4}. \tag{11}$$

Adopting for illustration $\theta = \psi/2 = 0.1$, $\xi_n = 1$, $\beta_w = 0.3$, we obtain $N_{cap} \simeq 3\times 10^{49}L_{51}^{5/4}$.

Now the fact that the avalanche growth is so rapid shows that the inwardly drifting neutrons may be converted back to having a 50 percent proton component shortly after crossing into the BPJ, and will merely line the BPJ outer boundary with a hot viscous sublayer (just as peripheral turbulent mixing would do). The short mean free path also means that relative Lorentz factor differences across it are likely to be much less than the total difference. The important assumption is that the inner side is exposed to contact with the more relaticvistic BPJ and is kept hot enough to have a free neutron component.

The picture we are led to by our basic model assumptions is a hot viscous sublayer with density decreasing inwards, and neutrons and protons coexisting in roughly equal numbers in the most tenuous regions. Below some density, the neutrons stream freely into the interior of the BPJ. Define the free streaming density n_{fs} to be that at which the proper hydrodynamic time $r/c\Gamma$ equals the proper collision time $\Gamma/n < \sigma v >$, i.e.

$$n_{fs} \equiv \Gamma^2 c/r < \sigma v > . \tag{12}$$

If the bulk Lorentz factor Γ is determined by the density of picked up neutrons then

$$\Gamma_{fs} = L_j/(n_{fs}mc^2\pi\theta^2r^2ch) = 26r_{12}^{-1/3}L_{j50}^{1/3}\theta^{-2/3}h^{-1/3} \tag{13}$$

where L_j is the BPJ luminosity and h is the specific enthalpy of the fluid in units of m_pc^2, and where we have used equation (12) in the last part of eq. (13). The free streaming density is

$$n_{fs} = (L_j/\pi\theta^2m_pc^3h)^{2/3}r^{-5/3}\sigma^{-1/3}. \tag{14}$$

The number of neutrons per unit time crossing the free streaming boundary inward within radius r is given roughly by

$$dN_{cr}/dt = \pi\theta r^2n_{fs}c/\Gamma = 8\times10^{49}r_{12}^{2/3}L_{j50}^{1/3}\theta^{1/3}h^{-1/3}s^{-1} \tag{15}$$

where we assume that the random component of the neutron velocity at the free streaming boundary is close to c. Thus, at $r_{12}\sim1$, most of the neutrons that diffused into the BPJ at $r_{10}\leq1$ are already free streaming.

When $n\gg n_{fs}$, h is assumed to be close to unity. In the free streaming zone, where $\Gamma\gg\Gamma_{fs}$, the neutrons are subjected to large shear in the BPJ, and as they move axisward, find themselves moving relative to the local frame at lab angle χ and nearly backward with a local Lorentz factor $\gamma'\sim\Gamma\Gamma_{fs}(1-\beta\beta_{fs}cos\chi)$. Thus h may be estimated as $\gamma'\sim\Gamma\Gamma_{fs}(1-\beta\beta_{fs}cos\chi)$ in the free streaming zone. At the free streaming surface, h is very geometry dependent, and can be between 1 and Γ_{fs}^2

The local spread of neutron velocities at the free streaming boundary is of order $1/\Gamma_{fs}$, so if $\theta\geq1/\Gamma$, the transverse velocity of an "inwardly" free streaming neutron may point away from the axis, as long as it does so less than the average local velocity, and $\chi\leq1/\Gamma_{fs}$. Some fraction($\sim1/e$) of the inwardly streaming neutrons will encounter further collisions, thus loading a "collisional annulus" of thickness $1/\Gamma_{fs}$ and radius θ, while the rest may continue further inward until they decay. If $\Gamma_{fs}^2\Delta t$, where Δt is the GRB duration, exceeds the neutron lifetime $900s\Gamma_{fs}$, then most of the neutrons decay within the fireball. Otherwise they decay behind it and leave a baryon pure core ahead.

The fluid parameters in the collisional annulus are similar to those described by Derishev and co-workers, where the radial acceleration just happens to proceed on a scale comparable to the mean collision time, inducing a modestly relativistic relative (radial) velocity between the neutrons and protons. In our picture, this apparent numerical coincidence is in fact natural for the annulus defined by marginally freely streaming neutrons. The annulus occupies $2/\theta\Gamma_{fs}\sim0.03r_{12}^{1/3}L_{j50}^{-1/3}\theta^{-1/3}h^{1/3}$ of the beam solid angle. For $\theta=0.1$ and $h^{1/3}\sim6$, this is comparable to the solid angle of the core, and suggests the possibility that many of the GRB we see are just these annuli. Nevertheless, the observational effects of a much higher Γ core are worth considering, especially because its elements can overtake the denser, peripheral neutron outflow.

It may be that the BPJ is collimated, and that its outer parts - or at least the inwardly free streaming neutrons - may eventually converge at the BPJ axis. The density can increase downstream and neutrons that have already passed through the free streaming boundary (according to the formal local definition) may then with high probability collide further downstream with impact angle $\chi \gg \Gamma_{fs}^{-1}$in a region of $\Gamma \gg \Gamma_{fs}$. (Even in the case of an asymptotically conical BPJ (Levinson and Eichler 2000), the fact that Γ_{fs} decreases with r means that neutrons free streaming inward from a point $r_1 \ll 10^{12}$cm, will graze those free streaming from further upstream at point $r_2 \leq 10^{12}$cm where $r_2 \geq r_1$. The impact angle as viewed in the lab frame is of order $\Gamma_{fs,2}^{-1}$.)

When $\chi \gg 1/\Gamma_{fs}$, freely axisward streaming neutrons are "broadsided" by faster interior plasma at impact angle $\chi \geq 1/\Gamma_{fs}$, and their optical depth to baryons in the interior plasma is *enhanced* by a factor $\theta^2\Gamma_{fs}^2$. Thus, the optical depth presented by axisward streaming neutrons to the interior plasma is at least of order unity and neutrino production by picked up particles is efficient. The energy of the neutrinos released in this avalanche is of order 0.05 of the typical proton energy.

The "top down" nature of pickup suggests that much energy can be dissipated in extremely energetic collisions. A high Γ flow that is slowed down by neutron pickup can be viewed as slowing down in stages, such that at each stage $\epsilon(r)dN/dt \sim L_j$, where $\epsilon(r)$ is the average energy per baryon at radius r and dN/dt, also a function of r, is the rate of pickup within radius r. For each new collisional pickup, about 50 percent of the original energy is dissipated into pion decay products, mostly neutrinos. (In each collision between a moving baryon and a target neutron, many pions are produced. The leading pion has about 0.2 of the original baryon energy, and the muon neutrino from its decay will have about 0.05 of the original, provided that the impact angle exceeds $1/\Gamma_{fs}$. Thus neutrinos of up to $\sim 0.05\epsilon$ will emerge, and they will contain about 5 percent of the jet energy. Another 10 percent or so is in the soft pions, which have a lab frame Lorentz factor somewhat larger but of order the center of mass Lorentz factor.) In the crude approximation that the neutrino losses are a small fraction of the collision energy, the spectrum of neutrinos is then $dN/dE \propto E^{-2}$ over a dynamical range that depends on how many optical depths the avalanche proceeds through; including neutrino losses leads to an even harder spectrum. Even if neutron pickup is extremely inefficient, this would still allow efficient neutrino emission in fewer, higher energy neutrinos. In the extreme scenario where there is only neutron decay and a single optical depth for collisions, there are about $6 \times 10^{49} c\Delta t/\tau_n\Gamma_{fs} \sim 10^{48}/\Gamma_{fs}$ neutrons that decay within the fireball. This suggests an asymptotic Γ of 10^4 and a maximum proton energy of $10^8 m_p c^2$. Most of this energy will be liberated as neutrinos over an optical depth of several. Note that for BPJ proton energies of order $10^8 m_p c^2$, even the soft pions can decay into $E \gg 1$ TeV neutrinos. Such extremely hard spectra would be a highly distinctive signature of the model, and the optical depth crossed by the avalanche would be manifested in the neutrino spectrum.

It is also instructive to view the problem from the point of view of a free streaming neutron. It has a better than even chance of not making another collision once entering the free streaming zone. However, the rare collision is with extremely relativistic plasma, and the energy liberated per collision goes as Γ^2. Writing the expected energy release per path length as $< dE/ds >= n < \sigma v > \Gamma^2$, and estimating Γ^2 as $L/\pi r^2 \theta^2 n$, we notice that $< dE/ds >$ is then independent of density, and much of the energy release can be in the form of rare but very energetic collisions.

A neutrino flux of $10^{52} F_{52}$ ergs could be detected at the one count level with a $1 km^2$ neutrino detector at a distance of $(F_{52} f)^{-1/2}$ Gpc, where f is the beaming factor. As noted earlier (Eichler and Levinson 1999, Meszaros and Waxman 2001), smothered GRB's could also be detected in (and only in) neutrinos.

5. Light Element Production

Light element production by spallation was discussed by Eichler and Letaw (1987) in regard to scenarios of UHE particle acceleration within supernovae ejecta. It was estimated that each cosmic ray would produce about 10 ^{10}B atoms from interaction with somewhat heavier nuclei, and that light element abundances constrain the average supernova to produce no more than about 10^{50} prompt cosmic rays in the midst of heavy nuclei. For a shock accelerated spectrum, the number density is dominated by GeV protons, and this would constrain the energy to less than 10^{48} ergs in cosmic rays. However, this would not apply to a spectrum of pickup ex-neutrals that is dominated by protons above 1 TeV. Also, an intense burst of particles on the same surface would produce "overkill" - i.e. light elements produced by spallation would then be further degraded by repeated spallation events. This is significant at a high energy particle fluence exceeding $10^{26} cm^{-2}$, though Rayleigh-Taylor instabilities at the head of the jet could lessen the overkill by constantly providing fresh surface.

Most important, however, is that a GRB-associated supernova is not typical. It may therefore be worth searching for excess light element lines in the young supernova remnants associated with GRB's. Enhancements of two orders of magnitude above the cosmic abundance could obtain. The original GRB-associated supernova, SN1998bw, had a remarkably large outflow velocity, c/6, suggesting that the ejecta may not have been particularly massive, and may have been preferentially close to the collimated fireball within.

While energetic protons which could be channeled away from enveloping material by electromagnetic forces might never interact with the surrounding ejecta, neutrons would easily penetrate the envelope if the ejecta collimate the GRB fireball, for then the walls of the BPJ curve inward.

6. Conclusions

We have worked out the details of an earlier suggestion that baryon loading of GRB fireballs is accomplished by pick-up ex-neutrons that crept across magnetic field lines into the path of the collimated fireball from the collimating material. For a GRB lasting, say, 30 seconds ($r_{12} \sim 1$), and having conical collimation θ, we find that there is a free streaming annulus at which the flow has a Lorentz factor Γ_{fs} of about $35 L_{50}^{1/4} (\theta/0.1)^{-1/2}$. (In this estimate we assumed that the specific enthalpy h, which is rapidly varying at this point, is roughly Γ_{fs}, and note that the result is only weakly dependent on it.) The thickness of the annulus is about $1/\Gamma_{fs}$, and $0.6(\theta/0.1)^{-1/2}$ of the solid angle within the cone of opening angle θ is subtended by the annulus. Well inside the annulus, i.e. when $\theta \gg 1/\Gamma$, the bulk Lorentz factor may be considerably higher, and the spectrum could be considerably harder. This suggests the possibility of extremely hard GRB's that might yield UHE photons and/or neutrinos, yet be relatively inconspicuous in soft γ-rays. Outside the annulus, the baryon loading is greater, Γ is considerably lower and this part of the outflow could be responsible for X-ray flashes (Berezinsky and Prilutsky, 1985), when the viewing angle happens to coincide with it. Prediction of a general angular distribution for observed GRB's is frustrated by our ignorance of the intrinsic distribution for all GRB's, as well as of the dependence of soft gamma ray efficiency on the amount of mass loading.

If the GRB is collimated by surrounding material, such as the envelope of a host star, enough that $\theta \leq \Gamma_{fs}$, then the transverse structure is much closer to being uniform.

The baryons in the fireball can, of course, then go on to generate further neutrinos downstream of their point of origin as in several previous discussions (Eichler 1994, Paczynski and Xu 1994, Waxman and Bahcall 1997). In this paper, on the other hand, we have presented a scenario for baryon loading whereby UHE neutrinos are a logical consequence. The neutrinos that result have individual energies of order $\Gamma^2 m_\pi \sim 10^{12-15}$ eV, which are easier to detect with large underwater and under-ice neutrino detectors than those at several GeV, which could result from differential acceleration of protons and neutrons by fireball pressure. They would have a very hard spectrum and be a highly distinctive feature of the pick-up model. Remarkably, the total energy output in neutrinos can in principle as high as that of the observed fireball, or even higher.

The ability to catch GRB-associated supernovae at an early stage should be greatly enhanced by SWIFT, and it may be possible to search for spallation-induced light element enhancement in the young supernova ejecta.

The emission of γ-rays from an annulus just inside an optically thick wall should give rise to a strongly polarized reflected component, as noted by EL. A quantitative discussion of this will be given in a subsequent paper.

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